

LORAN-C Tetraon Transponder and
Tracking System

(U.S.) National Oceanic and Atmospheric
Administration, Idaho Falls, ID

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Oct 86



EPA/600/3-86/060
October 1986

LORAN-C TETROON TRANSPONDER AND TRACKING SYSTEM

by

K. L. Clawson, E. F. Pound*, C. R. Dickson and G. E. Start
U. S. Department of Commerce
National Oceanic and Atmospheric Administration
Air Resources Laboratories Field Research Division
1750 Foote Drive
Idaho Falls, Idaho 83402
and
*E. F. P. Co.
1251 Cliffside Drive
Logan, Utah 84321

Interagency Agreement No. DW930033-01

Project Officer

John F. Clarke
Atmospheric Sciences Research Laboratory
Research Triangle Park, North Carolina 22771

ATMOSPHERIC SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 22771

ABSTRACT

An advanced system for tracking multiple regional scale Lagrangian markers (tetrooms with transponders) was developed. The system consists of a miniaturized tetroom-borne transponder and a small computerized receiving station capable of providing continuous real-time data on tetroom locations (latitude/longitude) and altitudes.

The package is composed of a tetroom-borne transponder and a ground-based or airplane-borne data acquisition system. The transponder is a compact, light-weight, inexpensive and expendable item. It consists of a telemetry subsystem, a LORAN-C receiver and a 403 MHz transmitter. The telemetry subsystem measures atmospheric temperature and pressure, converts the data into frequencies, and then transmits these data together with a transponder ID frequency to a receiving station in the bandwidth of 400.15-406.00 MHz. The transmitting frequency and transponder ID can be adjusted prior to tetroom launch to permit discrimination of multiple tetrooms at a range of up to 160 km. The 100 kHz LORAN-C signal received by the transponder is also transmitted simultaneously with the telemetry data by modulating the LORAN-C signal onto the telemetry signal. The transponder weighs less than 365 g including 3 C size lithium batteries. Transponder battery life is two days with AA batteries and 6 days with C size batteries. FAA regulation Part 101 governing unmanned free balloons is inapplicable since the weight to size ratio of the transponder plus batteries is less than 3.2 g cm^{-2} ($0.69 \text{ oz. in.}^{-2}$). This small size allows the transponder to be flown on a 1 m^3 tetroom.

The data acquisition system consists of an FM receiver with accompanying antenna and pre-amplifier system, a LORAN-C navigator, a frequency to digital converter, and a microcomputer. The receiving station is small enough to be mounted in a single engine aircraft or small van. The FM receiver, once tuned to a given transponder transmitting frequency, receives both the LORAN-C and telemetry signals. The telemetry signals are demodulated from the LORAN-C signal and is interpreted by the frequency to digital converter. The microcomputer then computes the height of the tetroom from temperature and pressure relationships. The LORAN-C navigator processes the LORAN-C signal and computes the location of the tetroom in terms of latitude and longitude. The location of the data acquisition system is not needed since the transponder retransmits the LORAN-C signal at the tetroom location. Published LORAN-C signal variations indicate that the largest position fix uncertainties for North America are expected to be less than $\pm 3.7 \text{ km}$.

The system was tested both in the laboratory and in the field. From these tests, the path and height uncertainties were determined to be $\pm 0.3 \text{ km}$ and $\pm 30 \text{ m}$, respectively. The system was demonstrated in CAPTEX '83; data obtained during that study are presented in accompanying appendices.

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ACKNOWLEDGMENTS

We thank Dr. John Clarke for his insightful review of this report and for his untiring patience during the development and revision of the LORAN-C transponder system.

We appreciate the assistance of Messrs. Gene White and Bob Heard during the development and testing stages of the system.

We also acknowledge the helpful assistance of Mr. Dave Gilmore and the staff at Beukers Laboratories, Hauppauge, NY, in an initial feasibility study of the LORAN-C tetraon transponder system during the fall of 1980.

Dr. Francis Pooler and Mr. Terry Clark reviewed the manuscript and provided helpful suggestions for improvements.

SECTION 1

INTRODUCTION

Considerable interest and concern exists regarding the source(s) of acid deposition and their precursors. Assessments of those sources, and indeed, even their identification, rests heavily upon an accurate knowledge and understanding of the regional scale movements of airborne pollutants. Most estimates of the movements of polluted air, and their previous locations (ultimately their sources), have been calculated from the widely-spaced, infrequent observations of upper-atmospheric winds. To date, evaluations of observed versus estimated air movements (trajectories) have resulted in inconsistent or generally disappointing comparisons. The selection of regional pollution abatement strategies and the assessment of cost-to-benefit factors could be grossly misleading in many situations when perceived through erroneous estimates of air movement.

The monitoring of those movements of air masses is important in gaining the needed understanding of the origin and predicting the fate of air pollution. One method of observing atmospheric trajectories and seeking the frequency and causes for erroneous trajectory estimates is the use of Lagrangian trajectories. One way to obtain these trajectories is to track the movement of constant volume balloons which have been released into the air mass of interest (Angell et al., 1971, 1975). These balloons, called tetroons (tetrahedral balloons) are superpressured to float at a specific atmospheric density level. Tetroons, launched with expendable transponders, have traditionally been tracked by ground-based radar deployed in a fixed and/or mobile mode (Angell et al., 1972; Reisinger and Mueller, 1983). This methodology offers a relatively inexpensive technique to examine, and hopefully improve, the fundamental understanding of where the pollution originated and how it moved as it passed across the various receptor locales.

The research and development activities reported herein focus upon the development and initial evaluations of a balloon trajectory marking system and the methodology for following it over regional scale distances. Briefly, the history of earlier tetroon systems and their performance are discussed in the following paragraphs.

Dickson and Pound (1961) built and tested a tetroon radar transponder which is still in use today. Unlike skin tracking, the transponder enables the radar to identify the tetroon in the presence of ground clutter. The system performs well within the 91 km M-33 radar tracking range with root mean square errors for range, azimuth and elevation being 15 m, 0.075° and 0.075°, respectively (Van der Hoven, 1968a). Actual relative path and height tracking uncertainties are a function of distance but are approximately ± 105 and ± 55 m, respectively (Van der Hoven, 1968b).

When it becomes desirable to follow tetroons to distances outside the tracking range of a radar such as the study described by Schiermeier et al. (1979), a series of radars must be established along the estimated tetroon trajectory. Usually two mobile radar units are employed in a "leap-frog"

arrangement where alternately one radar tracks the tetroon while the second radar is repositioned about 150 km further down the trajectory and then waits for the tetroon to come into tracking range. Occasionally, however, the tetroon may change course and then never comes into tracking range of the next radar. The repositioning process is, of course, time consuming, strenuous, and prone to error. At each new site, the tedious process of leveling the radar must be executed and the exact position of the unit must be determined. Because of these limitations, an advanced, highly mobile transponder tracking system is desired for application to extended local and regional-scale transport programs. Such a system would be an excellent aid to identifying trajectory paths of polluted air parcels, aid in aircraft sampling of those plumes, and could be used to track acid rain precursors across continents. We (Air Resources Laboratory Field Research Division of NOAA in cooperation with the E. F. P. Co.) have therefore, undertaken the task to develop such a transponder and receiving system.

SECTION 2

DEVELOPMENT HISTORY

Several different weather balloon tracking devices were investigated for use in this project. A tracking device based on the LORAN-C navigational signals appeared to be the most readily adaptable navigational system. LORAN-C or Long Range Aid to Navigation is a pulsed, low frequency radio-navigation system used by ocean-going vessels and commercial and private aircraft. The navigational signals are emitted on a carrier frequency of 100 kHz from transmitter chains and are propagated as both ground (which follow the surface of the earth) or sky (which bounce off the ionosphere) waves (Fig. 1). Transmission of the signal from each chain is coordinated from a single master station within each chain. The signals from each station in a given chain are time-delayed at preset intervals. The location of a given receiver is determined by the difference in arrival times of the various station signals. These time differences are measured in nanoseconds. The system is operated continuously by the U.S. Coast Guard and ground wave coverage includes all coastal waters and most of the inland area of the U.S. Within this area, location uncertainties are less than ± 38 m 95% of the time (Bowditch, 1977). Sky wave propagation fields include all of the U.S. but at position fix uncertainties of less than ± 3.7 km 95% of the time (*ibid.*). This error is acceptable since in a large-scale trajectory study on the order of 1000 km, the error would be less than 0.5% of the overall distance.

LORAN-C transponders have been used for several years for vertical balloon soundings (wind and temperature profiles of the troposphere and lower stratosphere) of about two hours duration. These LORAN-C transponder systems use a simple, highly-portable, tracking station. However, the LORAN-C transponders currently available are relatively large in size and require a large power supply. These features, coupled with a high power drain of the balloon-borne system, make these systems impractical for studies longer than a few hours. We therefore sought to improve this system to make it feasible to use for long-range trajectory studies.

Three different prototypes of the LORAN-C transponder and tracking system were developed and tested. The transmitter portion of the transponder was the focal point of the initial design work. It was desirable to emulate the transmitter portion of the radar transponders currently in use at this laboratory. These transponders have relatively low battery current drain because the transmitter is radar triggered by the signal emitted from the ground-based tracking system. Battery life is on the order of several weeks. Two low duty cycle systems with accompanying low battery current drain were considered for the LORAN-C transponder system.

PROTOTYPE #1

The first prototype consisted of a crystal controlled single sideband

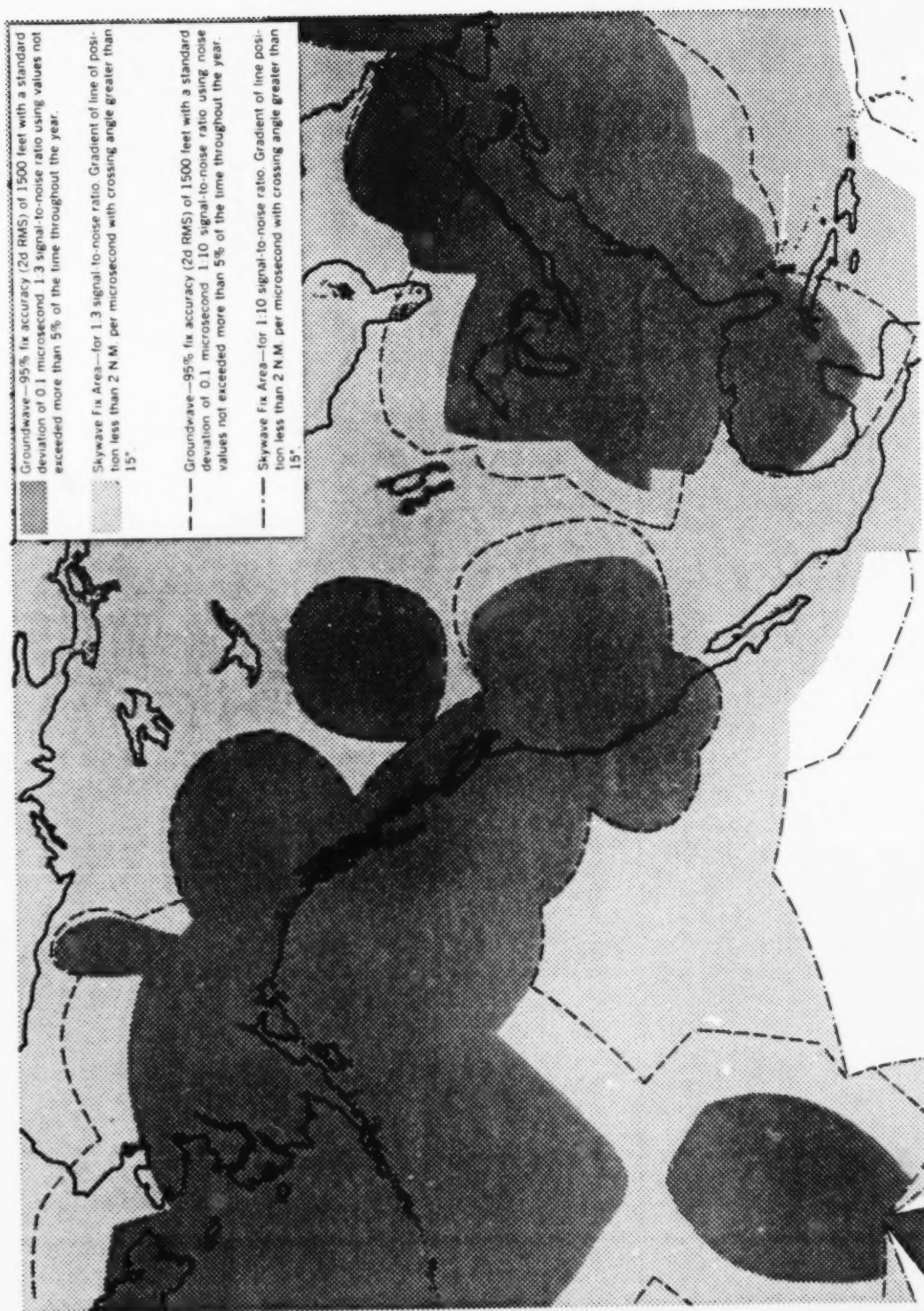


Fig. 1. LORAN-C reception ranges for North America.

transmitter with a reduced carrier to limit battery drain. A 100.75 MHz crystal oscillator was built together with a frequency multiplier and balanced mixer system to generate the single sideband signal. The system was tried only briefly. The continuous power required by the crystal oscillator and multiplier was greater than acceptable limits. It was also necessary to transmit the carrier signal along with the single side band to the tracking system in order to accurately frequency-lock the receiver. This required additional power drain. Furthermore, no commercial single side band receivers were available in the frequency range of the transmitter (400.15-406 MHz). All of the factors, when added to the complexity of the system, led to abandonment of this system in favor of the second approach.

PROTOTYPE #2

The second transponder prototype used the LORAN-C signal to turn on and off the transmitter. The normal 100 kHz LORAN-C signal, however, could not be directly used in this mode due to the presence of background noise. Hence, the LORAN-C signal was split into two channels, one wide-band and the other narrow-band. The narrow-band channel containing the noise filtered signal was amplitude detected and turned the transmitter on and off. The wide-band channel was delayed a few hundred microseconds and frequency modulated the transmitter. The tracking receiver detected the FM signal, recovered the original LORAN-C information and with a fast operating squelch system removed most of the noise when the transmitter was turned off. When tried, this system also had problems. The analog delay generator failed to operate properly at the 100 kHz LORAN-C frequency. It required a continuous power drain because of the high clock rate of the delay generator. For this reason, a modified second approach was tried. This modification consisted of the use of only half of the original amplitude modulated LORAN-C signal, along with a 100 kHz crystal oscillator and mixer to beat the LORAN-C signal to frequencies between 0 and 12.5 KHz. These frequencies were delayed using the original analog delay generator and were sent along with the 100 kHz pilot from the crystal oscillator to modulate the FM transmitter. This system was too complex to be used in mass production so the idea was shelved in favor of a third approach.

PROTOTYPE #3

The third transponder prototype used a very efficient, low-powered, continuous FM transmitter in conjunction with a very sensitive tracking receiver. The FM transmitter had an efficiency of 30% at 50 mW output. The corresponding receiver pre-amplifier system consisted of a gallium arsenide field effect transistor to lower the noise figure from 6 db to about 0.5 db. Thus the relatively low transmitter power was easily recovered by the sensitive receiving station. The receiver system was also portable and capable of being operated in a small single engine aircraft or rear seat of an automobile. Tests of the prototype transponder and tracking station from the long range trajectory study known as the Cross-Appalachian Tracer Experiment or CAPTEX '83 (Ferber et al., 1986), however, revealed areas for design improvement. The most notable flaw was with the transponder transmitter. Transmitter carrier frequency drift caused by large temperature changes was of such a magnitude that in some cases, the carrier

frequency drifted out of the reception range of the base station receiver. Power output of the transponder transmitter (50mW) also limited reception range to about 80 km. This design was then further modified to increase the transmitter output to 250 mW which doubled the reception range. Carrier frequency drift was also reduced. The base station receiver was also updated to current state-of-the-art technology with improved operating characteristics.

SECTION 3

TECHNICAL DESCRIPTION

The following paragraphs contain a detailed description of tetroom transponder and tracking system prototype number 3, with subsequent modifications. This prototype is the production model which is now useable for trajectory studies.

TRANSPONDER

The transponder package was designed to be an expendable item and is illustrated in Fig. 2. Each unit consists of three functional modules powered by three 3.4 V lithium batteries as shown in Fig. 3 and described in detail below: (1) a LORAN-C receiver, (2) a telemetry or house-keeping section, and (3) an FM transmitter. Lithium battery life expectancy is on the order of 2 days for AA size batteries and 6 days for C size batteries. The cost of the complete unit is about \$200.00. The transponder and AA batteries together weigh 260 g. Size C batteries add an additional 115 g mass to the transponder. The package is compact (50 mm dia., 235 mm long) and can be flown on a 1 m³ tetroom. FAA regulation Part 101 governing the operation of unmanned free balloons does not apply since the weight to size ratio is 3.2 g cm⁻² (0.69 oz. in.⁻²), about 1/4 the limit of 13.2 g cm⁻² (3 oz. in.⁻²). The total payload package weight is also much less than the overall limit of 1.8 kg. The requirement to (1) provide two balloon cutdown devices, (2) notify Air Traffic Control personnel of scheduled balloon launches and balloon positions every two hours after launch, and (3) equip the balloon with strobe lights for nighttime operation, among others, are avoided.

LORAN-C Receiver

The LORAN-C receiver receives 100 kHz LORAN-C signals from land-based transmitters via a 2.3 m flexible antenna. These signals are then amplified and modulate the FM transmitter for re-transmission to the base receiver. No other modification of the signal is made.

Telemetry Section

The telemetry section consists of a diaphragm type pressure transducer and a solid-state temperature sensor. Temperature output conforms to the following specifications:

Sensing range.	-20 to 55 °C
Accuracy	+0.5 °C
Linearity.	+0.3 °C
Response time over F.S..	10 s.

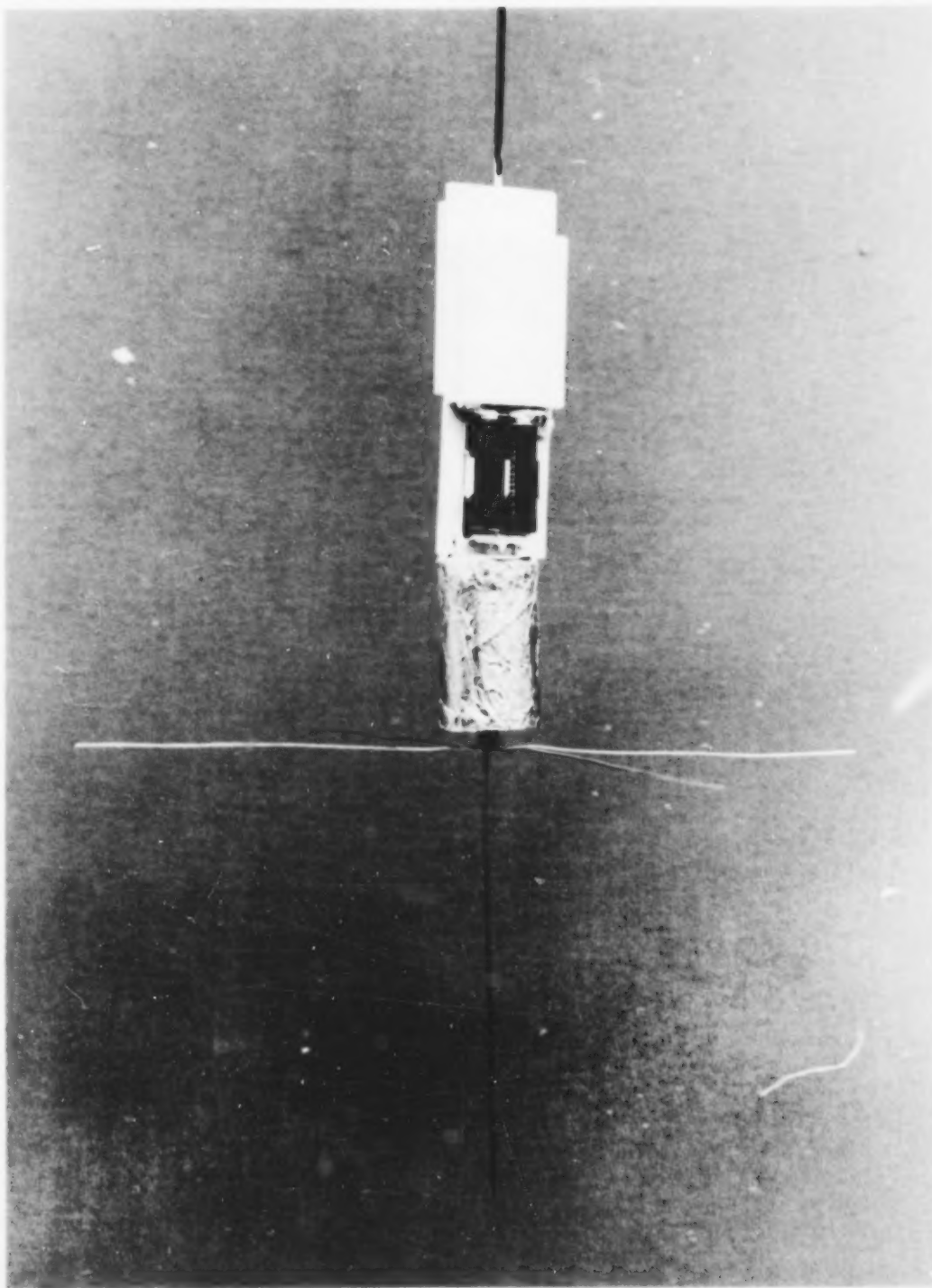


Fig. 2. LORAN-C tetraon transponder with LORAN-C receiving antenna (top), electronic package and batteries (center), and 403 MHz transmitting antenna (bottom).

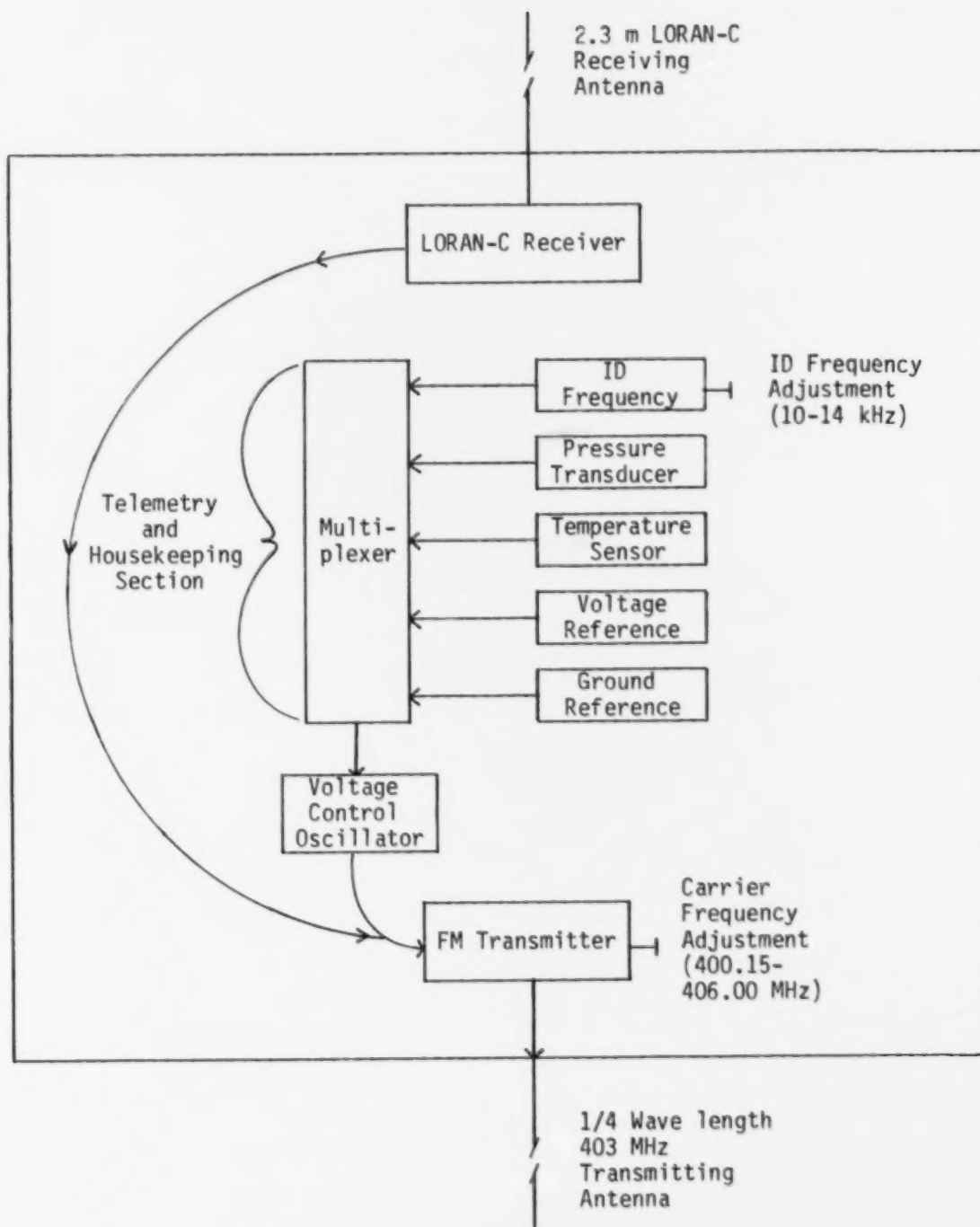


Fig. 3. Schematic depiction of the LORAN-C tetraon transponder.

The pressure output conforms to the following specifications:

Sensing range.	70 to 103 kPa
Accuracy	+0.1% of F.S.
Linearity.	$\pm 0.05\%$ of F.S.
Hysteresis	$\pm 0.05\%$ of F.S.
Response time over 10 to 90% of F.S. .	1 ms

Temperature sensitivity of the pressure transducer is compensated in the electronic circuit. Other house-keeping data are produced in the telemetry section. An identification (ID) voltage unique to each transponder is produced by an adjustable voltage regulator. This ID voltage aids in the identification of a given transponder when multiple tetroons are launched simultaneously. Full scale and ground reference voltages are also produced for voltage offset calculations made by the microcomputer at the receiving station. Voltage data from all of the components are multiplexed into a voltage control oscillator which modulates the FM transmitter. These five signals are continually produced with the complete cycle time of the multiplexer set at about 50 s. Each of the five signals is limited to a certain frequency range which allows for discrimination of each signal by the receiving station.

Transmitter

The FM transmitter modulates the LORAN-C signal and the telemetry data onto a carrier frequency in the range of 400.15 to 406.00 MHz for transmission to the base station. The carrier frequency of each transponder is adjusted prior to launch. This feature, plus the adjustable ID frequency together allow for additional discrimination of multiple tetroons launched simultaneously. A very stable carrier frequency is obtained without crystal control by utilizing a temperature compensation capacitor and a high Q tuned circuit. Carrier frequency drift is less than ± 0.5 MHz over a 20 °C temperature range. Transmitter power output is about 250 mW which does not cause major coupling and feedback problems and provides a transmission range of 160 km.

BASE STATION

The base or receiving station is shown in Fig. 4 and is schematically depicted in Fig. 5. It consists of an antenna, a pre-amplifier section, a 400.15 - 406.00 MHz FM receiver, a LORAN-C navigator, a frequency to digital converter, and a microcomputer for data acquisition and control. The most critical portion of the base station is the series of pre-amps which amplify the relatively small transponder signal which is limited to line-of-sight reception. All of the base station components are small enough to be mounted either in a small van or single engine airplane. The onetime acquisition costs of these components is about \$9000.00.

Antenna and Pre-amplifier

The antenna assembly is a 5/8 wave length solid antenna with matching pre-amp. The antenna must be mounted vertically on the underside of the



Fig. 4. LORAN-C base receiving station with receiving antenna and pre-amplifier assembly (left), and LORAN-C navigator, disk drive, frequency to digital converter, F1 receiver and microcomputer (right, top to bottom).

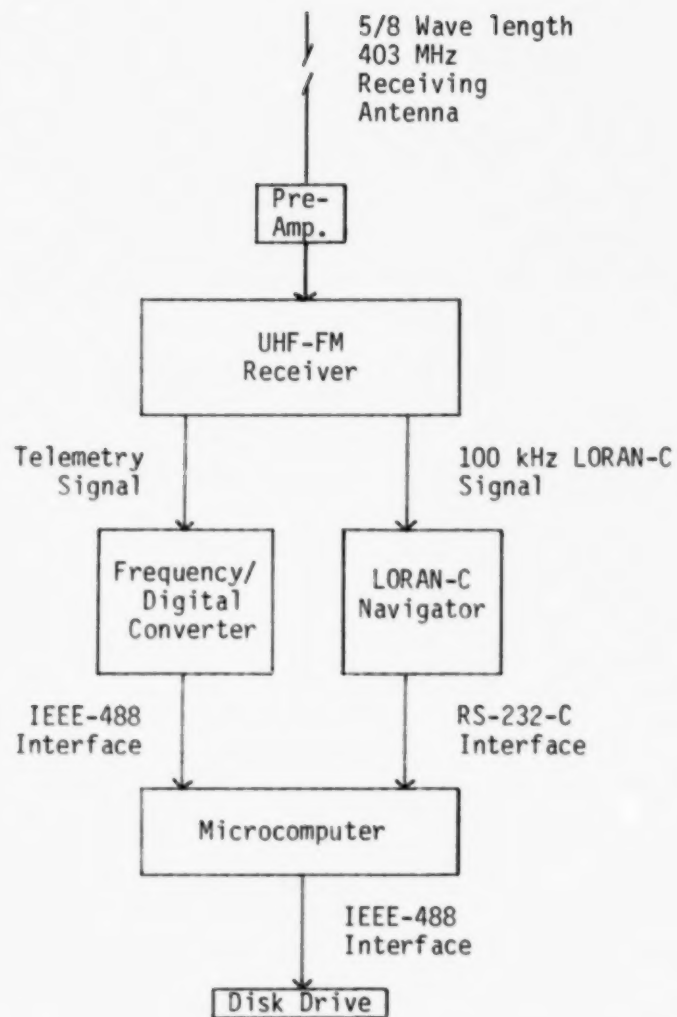


Fig. 5. Schematic depiction of the base receiving station.

airplane when airborne, in order to minimize airplane-to-ground radio communication interference. The pre-amp consists of a gallium arsenide field effect transistor which gives the antenna assembly a gain of approximately 20 db.

Receiver

The FM receiver is a UHF-FM receiver with the following general specifications:

Tuning Band	395 to 410 MHz
Noise Figure.	5 db
Image rejection	70 db minimum
Automatic Frequency Control Lock Range.	+3 MHz
Output Voltage.	1 V

The receiver is manually tuned to the transmitting frequency of a given transponder. It can be fine-tuned with the aid of an on-board tuning meter. Further signal quality control is provided to the operator from the visual output of an oscilloscope. The operator monitors the oscilloscope for any extraneous intermittent 403 MHz signals received from local transmitters and discards any erroneous data. Automatic frequency control (AFC) and RF gain is also adjustable. The receiver demodulates the 100 kHz LORAN-C and telemetry signals from the carrier frequency. The telemetry signal is sent to the data acquisition unit and the LORAN-C signal is sent to the LORAN-C navigator.

Frequency to Digital Converter

The commercially manufactured data acquisition unit receives the telemetry data as frequencies from the FM receiver. These low frequency modulations contain the following information from the transponder:

1. Identification reference
2. Barometric pressure
3. Temperature
4. Full scale voltage reference
5. Ground voltage reference

These frequencies are converted to digital signals and then sent via an IEEE-488 interface to the microcomputer. A sample output from the data acquisition unit is given in Table 1.

LORAN-C Navigator

The LORAN-C navigator is a commercially available LORAN-C receiver which incorporates an internal latitude and longitude computer. The internal computer converts the LORAN-C time differences provided by the FM receiver into latitude and longitude values. Time required for the navigator to lock on to the LORAN-C signal and provide reliable readings is approximately 2-5 min. These data are sent serially to the microcomputer.

Table 1. Typical transponder transmitted telemetry signals obtained from the data acquisition system using a 1 s gate time.

.	
.	
.	
66	Ground voltage reference
68	
6718	
12714	
12894	ID frequency
12896	
12896	
12896	
12896	
12894	
12810	
11482	
9960	Pressure frequency
9960	
9962	
9962	
9960	
9964	
9966	
11336	
5062	Temperature frequency
5058	
5058	
5056	
5056	
5058	
5058	
11932	
9008	Full scale voltage reference
9006	
9008	
9008	
9008	
9008	
9008	
11680	
66	Ground voltage reference
66	
66	
66	
66	
66	
6720	
12714	Pressure frequency
12714	
.	
.	
.	

Microcomputer

The system microcomputer processes both the telemetry and the latitude/longitude data sent to it from the data acquisition unit and the LORAN-C navigator through a series of BASIC programs detailed in Fig. 6. A master control program drives the slave or subprograms which are used to collect, print and store the data. Total time to acquire accurate data from a given transponder ranges from 5 to 10 min. Tetron heights are calculated in real time from temperature-pressure relationships using either the equation for the U. S. Standard Atmosphere or data from a local sounding, if available. Full details of the height calculation procedure are given in Appendix A. The data are also annotated with a date/time stamp obtained from the internal computer clock. The three dimensional path of the tetron can then be plotted from the program output.

ANCILLARY EQUIPMENT

Several other pieces of equipment serve as calibration and calculation aids. The pressure and temperature sensors of the transponder are calibrated prior to launch in a pressure/temperature chamber. This is done so that the pressure and temperature frequencies transmitted from the transponder can be converted into appropriate units of kPa and $^{\circ}\text{C}$, respectively. Calibration can be performed anytime before launch since the sensors do not deteriorate appreciably over several months. In practical use, the calibration should be performed in the laboratory before the start of the study. A calibration routine has been written for the same equipment used in transponder tracking. The FM receiver obtains the telemetry signal from the transponder located inside the calibration chamber in the same manner as in the tracking mode. The LORAN-C signal obtained simultaneously from the FM receiver is discarded since this portion of the transponder requires no calibration. The telemetry signal is then sent to the data acquisition unit and then on to the microcomputer after the appropriate frequency to digital conversions. In addition, the data acquisition unit obtains the simultaneous analog output of a thermocouple and lab standard pressure transducer located inside the chamber with the transponder. These data are converted to user units using the internal analog to digital converter in the data acquisition unit. An analysis of variance and a linear regression are performed on the pressure and temperature data for use in the tracking mode.

An additional subroutine was written for the microcomputer in order to obtain atmospheric soundings when the base receiving station is airborne. The accuracy of the tetron height calculation is improved if a local sounding is available. A sounding is obtained by mounting a pressure transducer and thermocouple externally on the airplane. Pressure and temperature are then monitored by the data acquisition unit at discrete height intervals as the plane ascends through the desired tetron flight layer. The internal analog to digital component of the data acquisition and the microcomputer subroutine convert the data into user units, which are stored for further use. The height, pressure and temperature of the local airport are also recorded. Tetron heights calculated from these locally acquired data are more accurate than those calculated from the U. S. Standard Atmosphere equation since simplifying assumptions of temperature change with height are included in the later (see Appendix A).

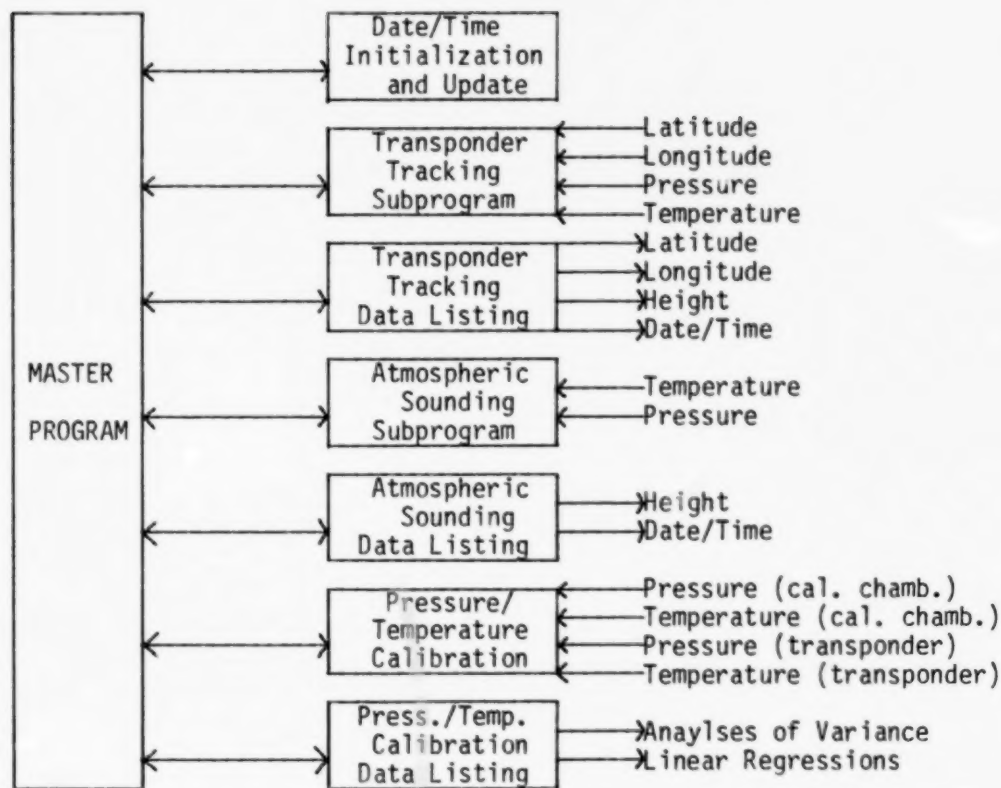


Fig. 6. Microcomputer program overview.

SECTION 4

SYSTEM EVALUATION

All transponder prototypes and tracking devices were tested to evaluate system performance. These tests included transponder performance and calibration checks in a pressure/temperature chamber, transponder position accuracy checks, transponder signal degradation checks, and base station reception range and system reliability. Transponder and receiving station prototypes which failed to perform satisfactorily were successively modified until adequate prototypes were designed. Transponder prototype #3 and corresponding tracking system passed initial tests and were subsequently tested during CAPTEX '83. The following discussion pertains to the evaluation of this transponder and receiving station.

LABORATORY TESTS

Transponder pressure and temperature sensor response were determined in a series of studies in the laboratory using a temperature/pressure chamber. Thirty transponders were tested by varying the temperature and/or pressure of the chamber and measuring the frequency output of each sensor.

Pressure Sensor

A typical pressure transducer calibration at ambient temperature (24 °C) is shown in Fig. 7. The calibration curve was found to be linear for all transponders tested. The average coefficient of determination (R^2) calculated from the analyses of variance was 0.9993. This indicates that the pressure transducer and companion electronic circuit are very reliable.

Temperature Sensor

A typical temperature sensor calibration at ambient pressure (85.5 kPa) for the temperature range from 15 to 55 °C is shown in Fig. 8. This calibration curve was also linear with an average R^2 calculated from the analyses of variance of 0.997. The temperature sensor appeared to be nearly as reliable as the pressure transducer.

LOCAL FIELD TESTS

Transponder-relayed LORAN-C signal accuracy and discrimination capability of the FM receiver were checked in two local field tests.

Transponder-relayed LORAN-C Signal Accuracy

Reliability and accuracy of the transponder relayed LORAN-C signals were

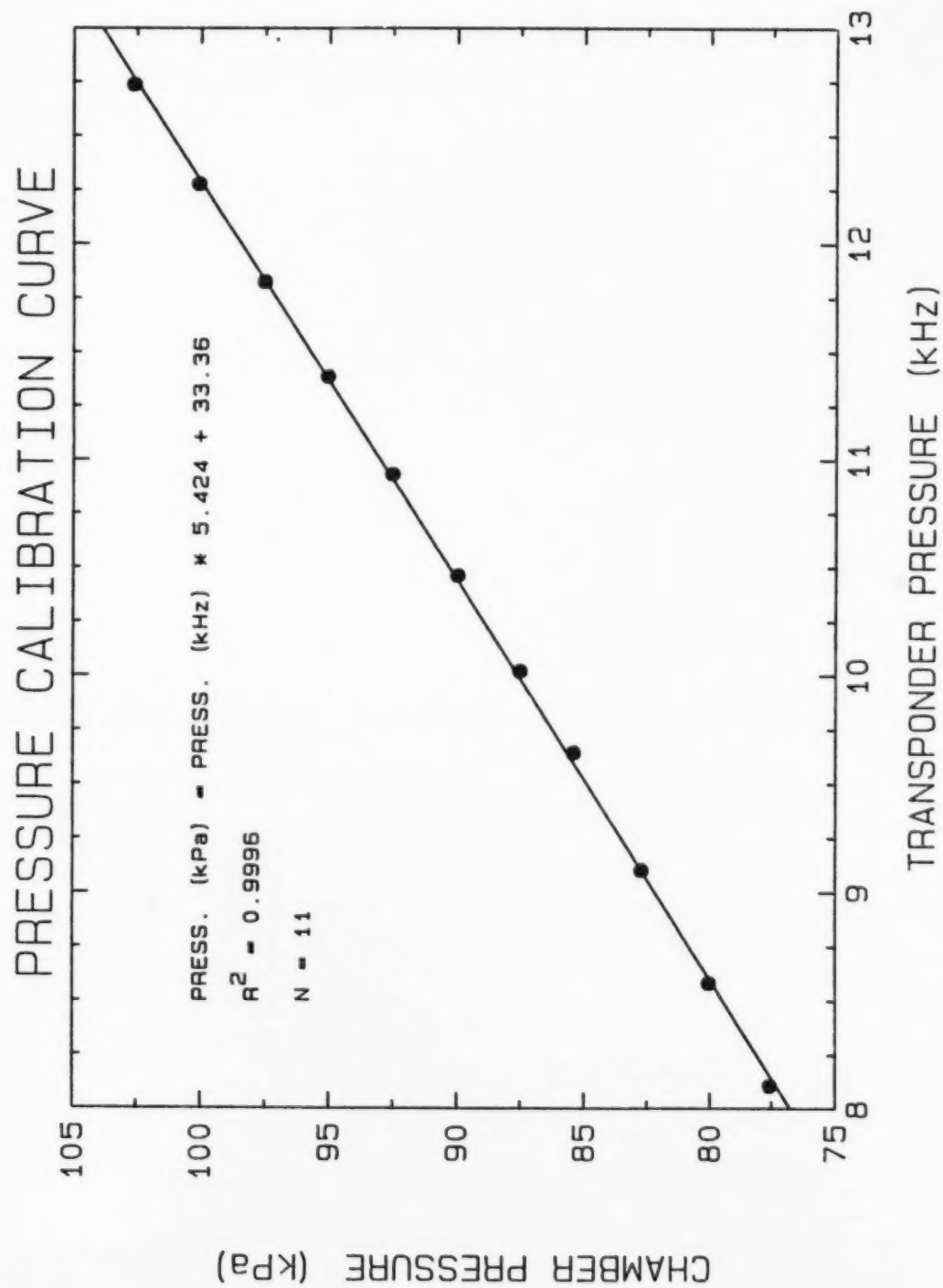


Fig. 7. Typical pressure transducer calibration.

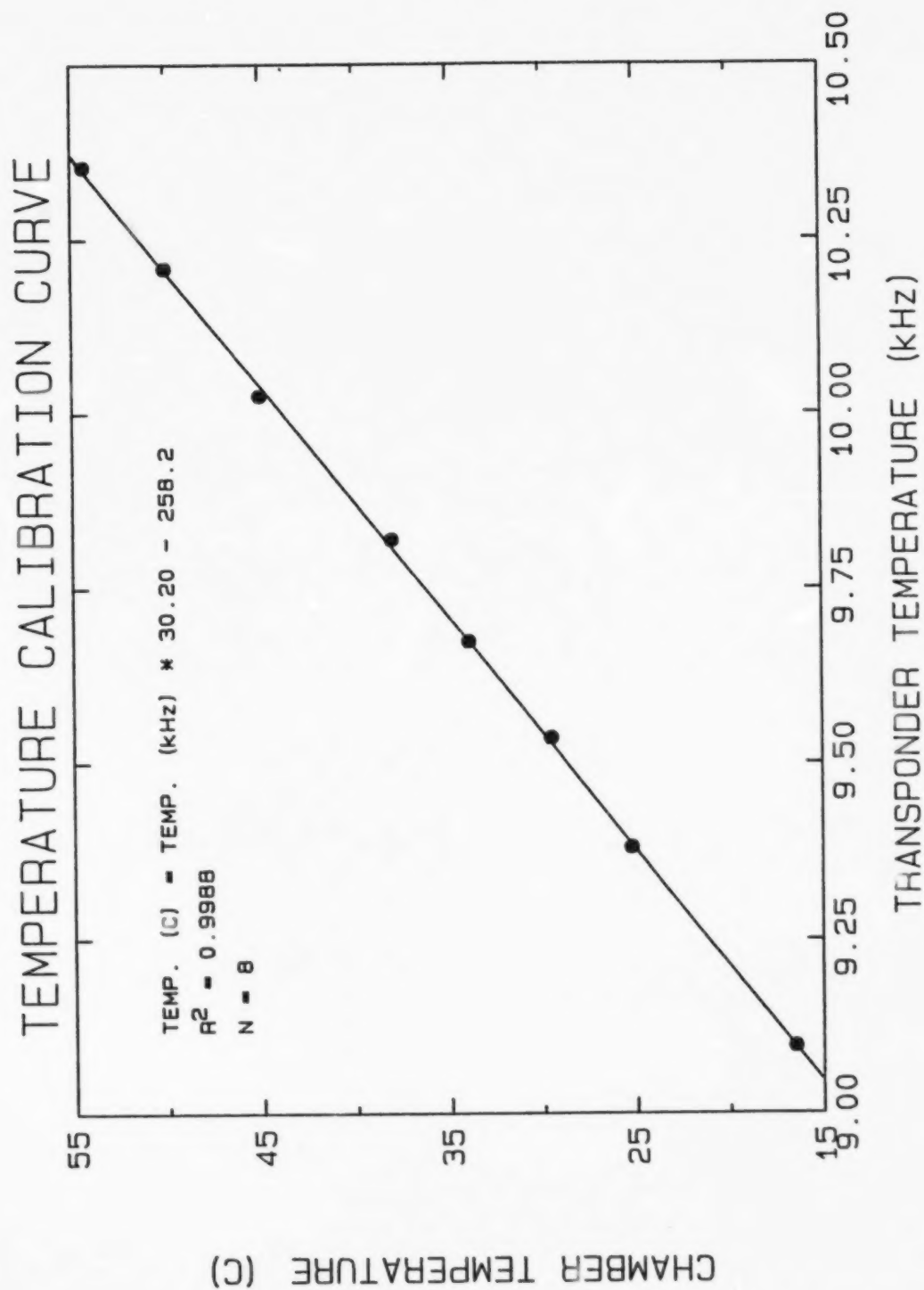


Fig. 8. Typical temperature sensor calibration.

checked by lifting a transponder with a tethered balloon to 100 m AGL and comparing the transponder LORAN-C output to that of a second ground-based LORAN-C receiver at the same location. The ground-based receiver and the transponder LORAN-C signals agreed with each other and the known latitude and longitude of the location to within 0.04 min latitude or longitude. Repeated checks showed no difference in compared LORAN-C readings.

Multiple Transponder Discrimination Capability

Discrimination capability of multiple transponders by the FM receiving station was checked by placing four transponders on a tethered balloon. The carrier frequency of each transmitter was tuned such that only 1 MHz separated each transponder from its nearest neighbor. Each transponder was easily distinguished from the other three in this mode regardless of distance to the receiver and LORAN-C and telemetry signals were correctly acquired. Hence, multiple targets launched simultaneously were expected to be easily followed.

OPERATION FIELD USE

Following local evaluations, the prototype transponder was used during CAPTEX '83 (September-October 1983). A total of 27 tetroons with accompanying transponders were launched and tracked from a dual engine airplane for various distances. Eighteen tetroons were released from Dayton, Ohio (39° 54.03' N, 84° 11.86' W) during the period 25 September through 17 October and again on 28 October. The remaining tetroons were released from a location near Sudbury, Ontario, Canada (46° 38.60' N, 80° 54.90' W). The tetroons were released in support of the diverse aspects of CAPTEX '83 and launched to various heights. On occasion, multiple tetroons were launched simultaneously. Appendices B, C and D contain full details on calibrations, atmospheric soundings and trajectories associated with the tetroon portion of CAPTEX '83. The most pertinent information is summarized in Table 2.

Single transponders were tracked almost continuously, except for refueling periods, during an entire test period. Transponder signals were detected and identified at ranges up to 80 km from the tracking aircraft. For multi-transponder tracking, the aircraft tracked a single tetroon for 15 to 30 minutes, then located and tracked another tetroon for another 15 to 30 minutes. Time required to lock-on to a transponder and to obtain reliable readings was from 5 to 20 minutes. Once locked-on, three to four readings were logged and plotted during the 15 to 30 minute tracking period. After reviewing the signals, those most consistent were printed and stored by the microcomputer.

Ten of the twenty-seven transponders were tracked for periods of greater than 10 hours. Five transponders were tracked for distances over 500 km, with one for a distance of nearly 1000 km. Trajectories typical of others obtained during the study are shown in Fig. 9 for 14 October. Some tetroons could have been tracked for longer time periods but were abandoned due to deteriorating weather conditions. Other tetroons launched near the ground became entangled in vegetation but their transponders continued to transmit for several days thereafter. Four transponders emitted intermittent signals of insufficient duration for accurate signal acquisition by the FM receiver

Table 2. Dates and times of tetroon releases, total distance tracked, total time tracked, and location of last position fix for CAPTEX '83. Tetroons released from 25 Sep-17 Oct and on 28 Oct were released from (D)ayton, Ohio (39° 54.03' N, 84° 11.86' W). The remaining tetroons were launched from (S)udbury, Ontario, Canada (46° 38.60' N, 80° 54.90' W).

Release Date and Location (mo/da)	Release Time (EDT)	Transponder Serial Number	Distance Tracked (km)	Duration of Pursuit (hr)	Final Location (Lat) (Lon)	
9/25 D	1300	5	120	3.6	40° 44.30' N	83° 27.40' W
9/30 D	0930	6	256	13.0	38° 01.72' N	85° 25.81' W
10/02 D	1500	12	480	17.7	40° 13.46' N	79° 26.47' W
	1630	13	43	2.1	40° 14.37' N	83° 48.09' W
	1630	2	19	2.4	40° 00.59' N	83° 59.08' W
	1800	3	240	6.4	40° 09.48' N	81° 34.72' W
10/06 D	1000	10	233	10.4	38° 27.36' N	81° 41.33' W
	1000	11	228	10.3	38° 25.01' N	81° 48.64' W
10/11 D	0900	16	640	13.1	45° 12.16' N	82° 31.94' W
10/14 D	1200	15	575	17.9	40° 40.32' N	76° 24.36' W
	1200	18	intermittent signal			
	1330	14	530	10.7	38° 29.59' N	77° 18.30' W
	1500	24	571	9.7	38° 48.15' N	76° 37.45' W
	1500	20	intermittent signal			
10/17 D	1600	8	4	1.0	39° 51.92' N	84° 10.71' W
	2200	25	11	3.4	39° 53.38' N	84° 20.90' W
	2200	17	intermittent signal			
10/19 S	1300	21	43	4.6	46° 12.82' N	81° 04.27' W
	2030	23	93	9.5	45° 40.87' N	81° 02.47' W
10/20 S	1500	19	360	10.4	47° 07.02' N	85° 06.76' W
	2000	28	19	1.0	46° 27.80' N	81° 01.80' W
10/26 S	1145	22	74	2.7	46° 15.87' N	79° 56.63' W
10/27 S	0245	27	123	4.3	45° 39.29' N	79° 44.17' W
10/28 D	1130	26	928	11.3	42° 23.58' N	74° 18.14' W
10/29 S	0200	29	394	15.3	42° 37.63' N	79° 43.04' W
	0300	30	intermittent signal			
	0500	--	signal not acquired			

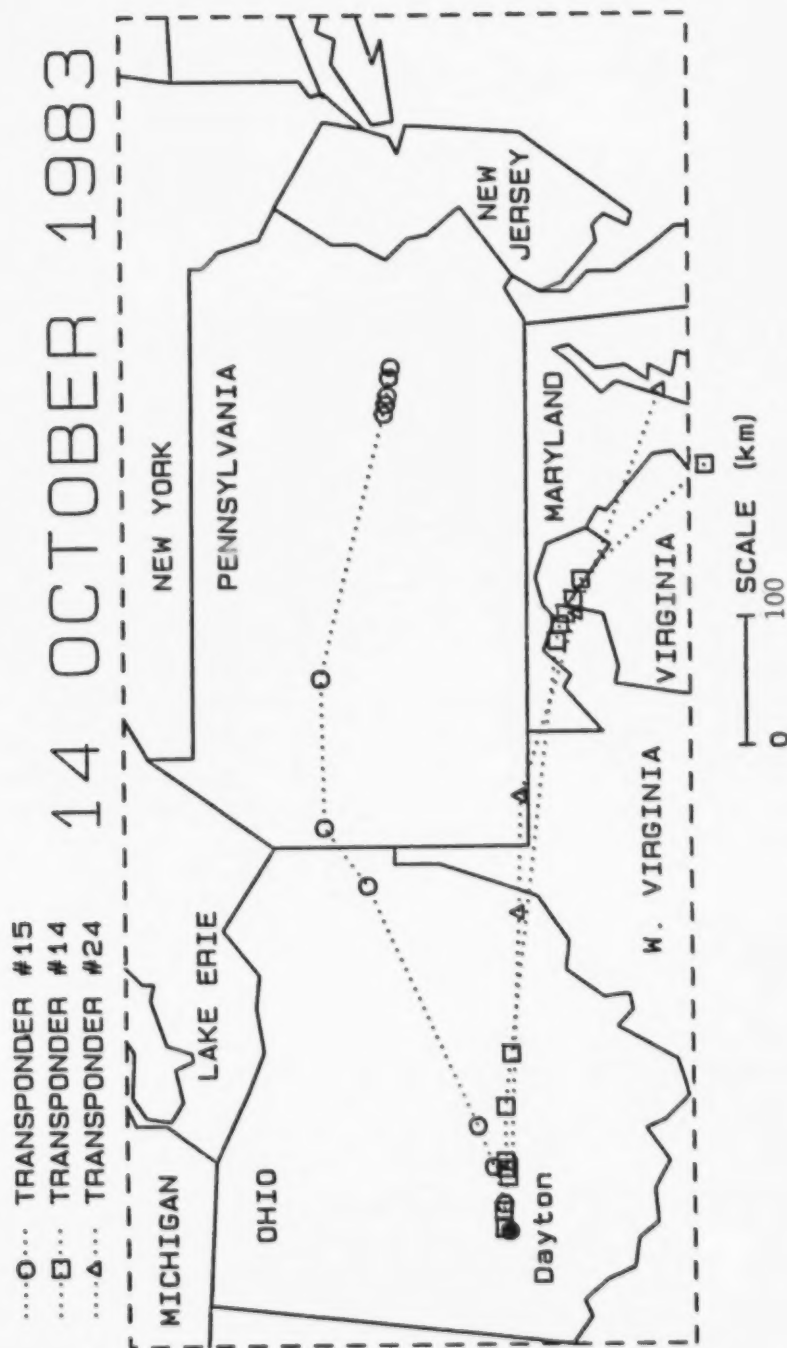


Fig. 9. Captex '83 tetron trajectories for 14 October.

due to the limited transmission range of the transponder. Tetrons released on 29 October were not within initial range of the airborne receiver station. The aircraft was positioned several hundred km east of the launch site in order to track the tetron released one day earlier. Estimated trajectory paths were calculated and the airplane flew an intercept path to those tetrons, but the signal from only one was acquired with sufficient accuracy to permit reliable tracking. In general, however, the transponders performed well with the exception of some carrier frequency drift and the seemingly small transmission range.

The LORAN-C tetron transponder tracking capability was independently determined on the afternoon of 11 October. The tetron released at 0900 EDT on that day was visually sighted over south-central Michigan by two aircraft crews participating in the study. The location and height of the tetron was verified by aircraft instrumentation, FAA radar contact with the aircraft, and visual observations of ground-based landmarks. Transponder relayed positions and heights were within 2 km and 30 m, respectively, of the independently determined positions and heights.

SUPPLEMENTARY TESTS

Following CAPTEX '83, the transponder was modified to minimize carrier frequency drift and increase transmission range. The transponder and tracking system were subsequently tested in 3 flights on 04 April 1986 for signal degradation and transmission range. The tracking system was mounted in a single engine aircraft while the transponder was suspended from a tethered balloon about 120 m above ground level. The test was conducted from 1100 to 1830 hours MST and consisted of a series of fly-aways from the transponder.

Results of the series of tests are listed in Table 3. Transmission range was observed to be about 160 km. All data collected within the 160 km radius was found to be strong and reliable. When the tracking station exceeded 160 km, the transmitted signal rapidly degraded into the background noise. The signal was easily reacquired after the tracking station returned to the 160 km limit.

Precision and accuracy of the LORAN-C navigator output was much less than the published worst-case LORAN-C position uncertainties. The largest deviation from true location ($43^{\circ} 30.61' \text{ N}$, $112^{\circ} 03.69' \text{ W}$) was 6.82 km obtained at 1124 hours when the airplane was only 37 km from the transponder. This was due to intermittent interference of the LORAN-C signal by some other local source. This was discriminated by an onboard oscilloscope. All other location errors were less than 2 km, even when the tracking station was located at 160 km from the transponder. The average error, excluding the 1124 data was 0.31 km with a standard deviation of 0.44.

Accuracy of the pressure and temperature sensors was impossible to determine since no other independent measures of these variables were available. Accuracy can be judged on the basis of the calibration checks, however. Precision can, on the other hand, be loosely determined from these data. The precision presented here is probably worse than that expected under controlled conditions since pressure and temperature probably varied over the course of the tests. Pressure, as obtained from the transponder, ranged from 83.40 to 83.70 kPa. Average pressure for the tests was 83.55 with a standard deviation of 0.097 kPa. Temperatures ranged from 11.1 to

Table 3. Transponder location (latitude, longitude, height), pressure and temperature as a function of receiving station distance. Distance error is relative to true transponder location (43° 30.61' N, 112° 03.69' W). Height is the U. S. Standard Atmosphere.

Time (MST)	Distance from Trans- ponder (km)	Latitude (Deg, Min)	Longitude (Deg, Min)	Distance Error (km)	Pressure (kPa)	Temper- ature (°C)	Height (m)
1117	19	43°30.63'N	112°04.08'W	0.52	83.65	11.1	1587
1124	37	43°27.60'N	112°06.60'W	6.82	83.70	11.6	1582
1135	56	43°30.61'N	112°03.66'W	0.09	83.62	11.6	1590
1154	74	43°30.59'N	112°03.66'W	0.13	83.60	11.8	1592
1206	93	43°30.60'N	112°03.66'W	0.15	83.68	12.0	1584
1443	44	43°30.61'N	112°03.72'W	0.09	83.54	12.0	1598
1453	93	43°30.63'N	112°03.66'W	0.00	83.48	12.4	1603
1702	50	43°30.61'N	112°03.72'W	0.09	83.45	11.1	1606
1715	83	43°30.60'N	112°03.84'W	0.26	83.59	12.8	1593
1721	124	43°30.60'N	112°03.72'W	0.15	83.48	12.1	1603
1728	148	43°30.60'N	112°03.72'W	0.15	83.50	12.0	1601
1741	167	-----signal lost-----		-----signal lost-----			
1746	160	43°30.81'N	112°03.60'W	0.44	83.40	11.1	1611
1800	148	43°30.40'N	112°04.86'W	1.61	83.45	11.8	1605
Average				0.81	83.55	11.9	1597
Standard Deviation				+1.85	+0.097	+0.47	+14.1

12.8 °C with an average of 11.9 ± 0.47 °C. Heights calculated from the pressure output using the U. S. Standard Atmosphere ranged from 1582 to 1611 m with the average height at 1597 ± 9.5 m. True ground level at the testing site was 1414 m. The error in heights is indicative of the inadequacy of the Standard Atmosphere equation to calculate elevation when lapse rates are not identical to the assumed rates. Elevation accuracy would be improved when atmospheric sounding data are available and other pressure/temperature relationships are used.

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

Development of a new LORAN-C transponder and receiving station has resulted in a product that is accurate, portable, and cost effective. The system assembled, tested, evaluated, and described herein has been developed using public funding provided, in part, through the sponsoring agency. Microcomputer programs and base receiving station and transponder schematics are available from the Director, Air Resources Laboratory Field Research Division, Idaho Falls, ID 83402.

The performance characteristics of this system are summarized below. The accuracy of the transponder package is excellent for trajectory studies and is much more portable than radar tracking devices currently in use. Local system tests indicated the path uncertainty to be ± 0.3 km for latitude and longitude and the height uncertainty to be ± 30 m. The worst-case path uncertainty should be less than 3.7 km, according to published LORAN-C data.

The base station (for tracking) may be utilized in several different modes. The selection of choices depends most upon the time and spatial scales of the application study and upon the costs of systems and tracking platforms. The choices of stationary receiving systems or mobile systems in a van or aircraft depend upon the technical needs of the study and upon the cost trade-offs of multiple systems, manpower, mobile system usage, reliability, etc. Each option is feasible in certain situations.

The transponder and receiving station show great potential for both long and short range tetraon tracking projects but is probably better suited for the former. The system is now useable without the need for further testing and is recommended for operation in future trajectory studies. Some future studies may include, as discussed previously, the tracking of acid rain precursors across continents as well as aid in the overall basic understanding of regional scale trajectories for meteorological purposes.

Recommendations for improvements on the system are limited to the suggestion to digitize the telemetry and housekeeping data onboard the transponder before it is transmitted to the base receiving station. Such an improvement would probably improve telemetry data integrity.

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)		
1. REPORT NO. EPA/600/3-86/060	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE LORAN-C TETROON TRANSPONDER AND TRACKING SYSTEM	5. REPORT DATE October 1986	6. PERFORMING ORGANIZATION CODE
	8. PERFORMING ORGANIZATION REPORT NO.	
7. AUTHOR(S) K.L. Clawson, E.F. Pound, C.R. Dickson, and G.E. Start	10. PROGRAM ELEMENT NO. CCVNIA/01 - 3084 (FY-87)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS National Oceanic and Atmospheric Administration Air Resources Laboratories Field Research Office 1750 Foote Drive Idaho Falls, Idaho 83402	11. CONTRACT/GRANT NO. IAG DW930033-01	
	13. TYPE OF REPORT AND PERIOD COVERED Final	
12. SPONSORING AGENCY NAME AND ADDRESS Atmospheric Sciences Research Laboratory-RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	14. SPONSORING AGENCY CODE EPA/600/09	
	15. SUPPLEMENTARY NOTES	
16. ABSTRACT An advanced system for tracking multiple regional scale Lagrangian markers was developed. The system consists of a miniature tetraon-borne transponder and a small computerized receiving station capable of providing continuous real-time data on tetraon location (latitude/longitude) and altitude. The transponder consists of a telemetry subsystem, a LORAN-C receiver, and a 403 MHz transmitter. The telemetry subsystem measures atmospheric temperature and pressure, converts the data into frequencies, and then transmits these data together with a transponder ID frequency to a remote receiving station. Multiple tetraons can be discriminated at a range of up to 160 km. The transponder weighs less than 365 g and can be flown on a 1 m ³ tetraon. Battery life is 2 to 6 days. The data acquisition system consists of an FM receiver, a LORAN-C navigator, a frequency to digital converter, and a microcomputer. The receiving station can be ground-based or mounted in a single engine aircraft. LORAN-C position fix uncertainty is 3.7 km. The system was tested both in the laboratory and in regional-scale field tests. The path and height uncertainties for those tests were ± 0.3 km and ± 30 m, respectively.		
17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 64
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE

DISCLAIMER

The information in this document has been funded in part by the United States Environmental Protection Agency under Interagency Agreement No. DW930033-01 to the United States Department of Commerce, National Oceanic and Atmospheric Administration. It has been subject to the Agency's peer and administrative review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement of recommendation for use.

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APPENDIX A

TETROON HEIGHT CALCULATION EQUATIONS

The method for calculating tetron heights is based on temperature, pressure and humidity relationships. Geometric height difference between two levels, according to Hess (1959), is expressed by

$$z_2 - z_1 = \frac{-R\bar{T}^*}{g} \ln \frac{P_2}{P_1} \quad (1)$$

where z is height (m), R is the gas constant for dry air ($287.04 \text{ J kg}^{-1} \text{ }^\circ\text{K}^{-1}$), $\bar{T}^*$ is the average absolute virtual temperature ($[\bar{T}^*_1 + \bar{T}^*_2]/2$, $^\circ\text{K}$) of the air layer between z_1 and z_2 , g is the acceleration of gravity (9.806 m s^{-2}), and P_1 and P_2 are atmospheric pressure (kPa) at z_1 and z_2 , respectively. Virtual temperature is a function of temperature and humidity which is expressed by

$$\bar{T}^* = \frac{1 + w/\epsilon}{1 + w} T \quad (2)$$

where w is the mixing ratio or the mass of water vapor per unit mass of dry air (kg kg^{-1}), ϵ is the ratio of the molecular weight of water vapor to dry air (0.622) and T is the absolute observed temperature ($^\circ\text{K}$). The presence of moisture in the air always increases $\bar{T}^*$ above T . However, the maximum difference between the two temperatures is always less than 7°K and is usually less than 1°K (Hess, 1959).

For the purpose of calculating tetron heights, Eqn. 1 is used in two different forms, depending on the amount and type of data available. If no other data are available other than the temperature and pressure acquired from the transponder, the U. S. Standard Atmosphere is used for altitude determination. The equation specifying this atmosphere is a special case of Eqn. 1, and is derived when the following assumptions are made:

1. The temperature and pressure at sea level are 288°K (15°C) and 101 kPa , respectively.
2. The air is dry and obeys the ideal gas law.
3. The lapse rate ($\Delta T/\Delta z$) is constant at $6.5^\circ\text{K km}^{-1}$.

Eqn. 1 then simplifies to

$$z_2 = 44308 \left[1 - \left(\frac{P_2}{101.325} \right)^{0.19026} \right] \quad (3)$$

and requires only pressure for the height calculation.

None of the above stated assumptions can always be met in the real atmosphere and altitude calculation errors from the U. S. Standard

Atmosphere can be substantial. A second form of Eqn. 1 is therefore preferred when the temperature and pressure of discrete air layers below the tetroon are known. These temperatures and pressures can be obtained by the airborne data acquisition system as the airplane ascends from the surface to the tetroon flight altitude. The temperature, pressure and altitude of the surface are also required. Eqn. 1 is then used to calculate the height of the top of each succeeding air layer for which temperature and pressure are measured from the surface up to and including the layer at the tetroon flight altitude. Average absolute temperature ($\bar{T}^*$) is also assumed to equal the average absolute observed temperature ($\bar{T}$). Since the temperature difference between T^* and T is less than 1 °K, the introduced error in the calculated height is small.

In summary, two methods of calculating tetroons heights are employed depending on the type of data available. Each method is suitable for height calculations; however the method which uses atmospheric sounding data is preferred over use of the U. S. Standard Atmosphere.

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APPENDIX B

CAPTEX '83 TETROON TRANSPONDER PRESSURE TRANSDUCER CALIBRATIONS

Transponder S/N: 2

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.970	99.80	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.593 + 26.99$ $R^2 = 0.9993$ $P < 0.001$
12.060	94.12	
11.227	89.73	
10.465	85.50	
9.831	82.04	
9.662	81.11	

Transponder S/N: 3

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
6.130	98.67	$\text{Press. (kPa)} = \text{Press. (kHz)} * 11.05 + 31.10$ $R^2 = 0.9994$ $P < 0.001$
5.352	90.52	
4.820	84.47	
4.544	81.31	
4.362	79.12	

Transponder S/N: 5

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
11.572	96.20	$\text{Press. (kPa)} = \text{Press. (kHz)} * 6.012 + 26.86$ $R^2 = 0.9989$ $P < 0.05$
9.078	81.60	
8.565	77.90	

Transponder S/N: 6

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
11.866	98.70
10.688	92.33
10.000	88.29
9.333	84.44
8.595	79.96
8.154	77.27

Regression Statistics

$$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.789 + 30.26$$

$$R^2 = 0.9994$$

$$P < 0.001$$

Transponder S/N: 8

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
12.634	97.06
11.628	93.69
10.818	89.22
9.964	84.39
9.310	80.63
8.868	77.93

Regression Statistics

$$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.606 + 28.42$$

$$R^2 = 0.9996$$

$$P < 0.001$$

Transponder S/N: 10

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
12.414	99.45
11.602	95.38
10.858	91.43
9.778	85.53
9.198	82.37
8.664	79.36

Regression Statistics

$$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.372 + 32.95$$

$$R^2 = 0.9997$$

$$P < 0.001$$

Transponder S/N: 11

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
10.314	93.26	$\text{Press (kPa)} = \text{Press. (kHz)} * 5.264 + 39.01$ $R^2 = 1.0000$ $P < 0.001$
9.674	89.99	
8.926	85.98	
8.276	82.58	
7.638	79.20	

Transponder S/N: 12

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.298	99.10	$\text{Press (kPa)} = \text{Press. (kHz)} * 5.604 + 30.35$ $R^2 = 0.9996$ $P < 0.001$
10.972	91.98	
10.168	87.47	
9.244	82.25	
8.390	77.18	

Transponder S/N: 13

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.598	99.02	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.456 + 30.37$ $R^2 = 0.9993$ $P < 0.001$
11.372	92.67	
10.410	86.89	
9.546	82.58	
8.860	78.68	

Transponder S/N: 14

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
11.992	97.70	$\text{Press (kPa)} = \text{Press. (kHz)} * 5.262 + 34.98$ $R^2 = 0.9984$ $P < 0.001$
10.902	92.52	
10.277	89.38	
9.460	85.04	
8.692	80.70	
8.062	77.07	

Transponder S/N: 15

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.054	98.53	$\text{Press. (kPa)} = \text{Press. (kHz)} * 4.800 + 40.67$ $R^2 = 0.9929$ $P < 0.001$
11.994	97.63	
9.910	89.16	
9.210	85.39	
8.240	79.94	
7.718	77.19	

Transponder S/N: 16

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.300	97.96	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.254 + 33.57$ $R^2 = 0.9994$ $P < 0.001$
11.406	93.64	
10.184	87.31	
9.120	81.52	
8.308	77.03	

Transponder S/N: 17

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.202	97.72	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.574 + 29.90$ $R^2 = 0.9995$ $P < 0.001$
11.226	92.62	
10.466	88.37	
9.858	84.95	
9.338	81.94	
8.942	79.56	

Transponder S/N: 18

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.344	97.80	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.478 + 30.32$ $R^2 = 0.9997$ $P < 0.001$
11.426	93.03	
10.690	88.98	
10.082	85.64	
9.482	82.28	
8.964	79.30	

Transponder S/N: 19

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.194	97.84	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.821 + 27.04$ $R^2 = 0.9996$ $P < 0.001$
11.368	93.28	
10.612	88.97	
9.858	84.57	
8.590	76.87	

Transponder S/N: 20

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.928	97.98	$\text{Press. (kPa)} = \text{Press. (kHz)} * 4.724 + 37.07$ $R^2 = 0.9996$ $P < 0.001$
11.638	92.22	
10.582	87.18	
9.670	82.77	
8.904	79.00	

Transponder S/N: 21

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.260	97.46	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.797 + 26.53$ $R^2 = 0.9997$ $P < 0.001$
11.502	93.26	
10.940	90.05	
10.366	86.71	
9.794	83.31	
9.302	80.32	

Transponder S/N: 22

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
12.172	97.47
11.316	92.76
10.616	88.63
10.028	85.17
9.526	82.14
9.064	79.30

Regression Statistics

$$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.856 + 26.36$$

$$R^2 = 0.9996$$

$$P < 0.001$$

Transponder S/N: 23

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
12.150	97.50
11.390	93.25
10.726	89.50
10.196	86.34
9.662	83.10
9.250	80.59

Regression Statistics

$$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.834 + 26.76$$

$$R^2 = 0.9997$$

$$P < 0.001$$

Transponder S/N: 24

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
12.206	97.43
11.456	93.47
10.800	90.00
10.238	86.90
9.710	83.94
9.166	80.80

Regression Statistics

$$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.462 + 30.88$$

$$R^2 = 0.9997$$

$$P < 0.001$$

Transponder S/N: 25

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.160	97.45	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.545 + 30.16$ $R^2 = 0.9997$ $P < 0.001$
11.408	93.41	
10.804	90.22	
10.178	86.68	
9.772	84.42	
9.338	81.93	
8.952	79.63	

Transponder S/N: 26

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.302	97.53	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.308 + 32.38$ $R^2 = 0.9996$ $P < 0.001$
11.492	93.40	
10.826	90.00	
10.104	86.13	
9.548	83.06	
8.952	79.74	

Transponder S/N: 27

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>	<u>Regression Statistics</u>
12.176	97.53	$\text{Press. (kPa)} = \text{Press. (kHz)} * 5.637 + 29.05$ $R^2 = 0.9997$ $P < 0.001$
11.324	92.96	
10.578	88.79	
9.994	85.47	
9.462	82.38	
8.994	79.60	

Transponder S/N: 28

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
12.418	97.80
11.592	93.11
10.980	89.60
10.396	86.07
9.880	83.10
9.406	80.37
9.048	78.12

Regression Statistics

Press (kPa) = Press. (kHz) * 5.835 + 25.43
 $R^2 = 0.9999$
 $P < 0.001$

Transponder S/N: 29

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
11.344	92.89
11.044	91.24
10.830	90.07
10.500	88.25
9.560	83.08
8.855	79.20

Regression Statistics

Press (kPa) = Press. (kHz) * 5.501 + 30.49
 $R^2 = 1.0000$
 $P < 0.001$

Transponder S/N: 30

<u>Transponder Pressure (kHz)</u>	<u>Chamber Pressure (kPa)</u>
12.165	97.66
10.584	88.82
10.111	86.17
9.572	83.16
9.146	80.78

Regression Statistics

Press (kPa) = Press. (kHz) * 5.592 + 29.64
 $R^2 = 1.0000$
 $P < 0.001$

APPENDIX C

CAPTEX '83 ATMOSPHERIC SOUNDINGS

Date: 25 September 1983
Location: Above Dayton VOR

<u>TIME</u> <u>(HHMMSS,</u> <u>EDT)</u>	<u>TEMPERATURE</u> <u>(°C)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above</u> <u>m.s.l.)</u>
130001	24.10	99.52	387
130020	20.44	96.55	653
130043	19.31	95.27	771
130130	18.00	93.71	915
130203	16.90	92.44	1071
130230	15.84	90.66	1230
130300	14.71	88.75	1385
130334	13.40	87.15	1541
130422	13.20	85.57	1698
130514	12.31	82.45	2016
130609	11.90	80.18	2255
130631	11.30	79.24	2355
130700	10.36	77.98	2491
130750	9.03	76.47	2657

Date: 26 September 1983
Location: Above Dayton VOR

<u>TIME</u> <u>(HHMMSS,</u> <u>EDT)</u>	<u>TEMPERATURE</u> <u>(°C)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above</u> <u>m.s.l.)</u>
030002	18.47	98.96	307
030425	19.58	95.82	592
030545	17.53	92.11	934
030653	14.68	88.99	1231
030805	12.20	85.94	1529
030949	11.07	85.74	1549

Date: 02 October 1983
Location: Above Dayton VOR

<u>TIME</u> (HHMMSS, EDT)	<u>TEMPERATURE</u> (°C)	<u>PRESSURE</u> (kPa)	<u>ALTITUDE</u> (m above m.s.l.)
095016	12.83	80.85	2017
095231	14.13	82.58	1835
095552	15.42	84.06	1681
095829	16.70	85.53	1532
100046	18.20	87.19	1364
100337	19.55	88.77	1207
100558	20.60	90.37	1051
100843	22.09	92.09	884
101144	23.25	93.65	737
101419	24.05	95.35	577

Date: 02 October 1983
Location: Above Dayton VOR

<u>TIME</u> (HHMMSS, EDT)	<u>TEMPERATURE</u> (°C)	<u>PRESSURE</u> (kPa)	<u>ALTITUDE</u> (m above m.s.l.)
101826	24.05	95.35	904
101901	23.25	93.65	1064
101945	22.09	92.10	1211
102102	20.60	90.38	1377
102135	19.55	88.77	1534

Date: 11 October 1983
Location: Above Dayton VOR

<u>TIME</u> <u>(HHMMSS,</u> <u>EDT)</u>	<u>TEMPERATURE</u> <u>(°C)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above</u> <u>m.s.l.)</u>
091049	12.77	98.55	307
091129	12.11	98.19	338
091212	14.30	95.94	538
091239	14.99	94.13	703
091312	14.79	92.44	859
091347	14.20	90.75	1018
091426	13.29	89.10	1175
091458	12.02	87.49	1332
091536	10.93	85.88	1490
091621	10.04	84.29	1647
091705	8.99	82.71	1808
091734	8.61	81.87	1894
091841	6.69	79.58	2132
091920	4.82	79.02	2192
092007	4.53	76.67	2424
092521	4.50	75.11	2595
092550	3.13	73.71	2751
092623	1.85	72.37	2902
092718	1.09	70.96	3064

APPENDIX D

CAPTEX '83 TETROON TRACKING DATA

DAYTON, OHIO TETROON RELEASE

25 September 1983

Transponder S/N: 5
Launch Time: 1300 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1400	40°03.90'N	84°05.48'W	---	---
1433	40°10.76'N	83°59.82'W	---	---
1633	40°44.30'N	83°27.40'W	---	---

DAYTON, OHIO TETROON RELEASE

30 September 1983

Transponder S/N: 6
Launch Time: 0930 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1010	39°48.26'N	84°19.84'W	---	---
1026	39°45.56'N	84°22.71'W	---	---
1130	39°34.12'N	84°35.65'W	90.50	953
1512	39°11.97'N	85°03.03'W	---	---
1525	39°10.13'N	85°04.95'W	88.80	1102
1527	39°09.71'N	85°05.44'W	88.90	1094
1534	39°09.18'N	85°06.09'W	88.60	1114
1539	39°08.60'N	85°06.10'W	88.40	1134
1543	39°08.22'N	85°06.41'W	89.22	1060
1549	39°07.42'N	85°06.85'W	88.50	1122
1558	39°06.63'N	85°06.75'W	87.90	1180
1608	39°05.31'N	85°06.70'W	88.35	1141
1613	39°04.75'N	85°06.88'W	88.80	1100
2155	38°08.57'N	85°22.13'W	96.50	406
2208	38°07.17'N	85°22.90'W	96.60	413
2212	38°05.27'N	85°23.18'W	96.27	430
2232	38°01.72'N	85°25.18'W	96.80	393

DAYTON, OHIO TETROON RELEASE

02 October 1983

Transponder S/N: 12
Launch Time: 1500 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1502	39°54.03'N	84°11.86'W	---	---
1524	39°56.50'N	84°07.84'W	87.50	1213
1535	39°56.93'N	84°06.61'W	81.60	1738
1538	39°57.78'N	84°04.80'W	89.90	1790
1558	39°59.42'N	83°59.38'W	81.17	1773
1625	40°01.00'N	83°47.91'W	81.10	1780
1738	40°02.48'N	83°51.48'W	81.08	1781
1742	40°02.58'N	83°51.52'W	81.11	1778
2328	39°55.71'N	81°42.61'W	84.10	1515
2342	39°55.25'N	81°40.92'W	83.80	1542
0822	40°12.36'N	79°34.02'W	82.70	1639
0836	40°13.17'N	79°28.30'W	82.46	1659
0844	40°13.46'N	79°26.47'W	82.28	1676

Transponder S/N: 13
Launch Time: 1630 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1654	39°57.31'N	84°09.46'W	96.70	397
1831	40°14.07'N	83°49.48'W	96.10	460
1833	40°14.37'N	83°48.99'W	95.80	482

Transponder S/N: 2
Launch Time: 1630 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1639	40°03.02'N	84°02.57'W	84.00	1519
1720	40°01.60'N	84°03.03'W	83.50	1568
1851	40°00.59'N	83°59.08'W	76.50	2311

DAYTON, OHIO TETROON RELEASE

02 October 1983
(Con't)

Transponder S/N: 3
Launch Time: 1800 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1816	39°56.74 'N	84°09.46 'W	83.50	1570
1846	40°00.42 'N	83°59.78 'W	---	---
1854	40°01.09 'N	83°57.44 'W	78.50	2007
2210	40°07.32 'N	82°39.38 'W	80.40	1843
2226	40°07.26 'N	82°41.76 'W	80.90	1798
0026	40°09.48 'N	81°34.72 'W	81.30	1764

DAYTON, OHIO TETROON RELEASE

06 October 1983

Transponder S/N: 10
Launch Time: 1000 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1146	39°29.85'N	83°32.85'W	87.04	1256
1202	39°27.19'N	83°27.04'W	87.09	1252
1413	39°09.99'N	82°55.87'W	87.00	1261
1417	39°09.55'N	82°55.15'W	87.00	1261
1420	39°09.36'N	82°54.81'W	86.97	1263
1427	39°08.85'N	82°53.25'W	87.27	1236
1430	39°08.57'N	82°52.56'W	87.51	1216
1434	39°08.17'N	82°51.42'W	87.50	1216
1454	39°04.72'N	82°46.44'W	87.54	1213
1803	38°47.91'N	82°08.74'W	94.45	606
2025	38°27.36'N	81°41.33'W	95.70	494

Transponder S/N: 11
Launch Time: 1000 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1046	39°41.32'N	83°52.21'W	92.30	793
1139	39°31.44'N	83°35.48'W	91.98	821
1149	39°28.67'N	83°32.05'W	91.68	849
1156	39°27.38'N	83°29.17'W	91.20	891
1405	39°09.81'N	82°56.19'W	91.45	870
1410	39°09.61'N	82°55.95'W	91.70	846
1443	39°05.79'N	82°48.75'W	91.68	849
1445	39°05.55'N	82°48.26'W	91.86	831
1447	39°05.35'N	82°47.81'W	91.77	839
1752	38°43.71'N	82°10.76'W	92.67	760
2015	38°25.01'N	81°48.64'W	95.30	526

DAYTON, OHIO TETROON RELEASE

11 October 1983

Transponder S/N: 16
Launch Time: 0900 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
0950	39°57.53'N	84°11.11'W	95.50	512
1002	40°00.18'N	84°11.03'W	84.60	1473
1022	40°04.51'N	84°11.65'W	77.60	2087
1029	40°05.12'N	84°12.38'W	75.80	2378
1051	40°11.81'N	84°12.69'W	76.60	2300
1109	40°17.56'N	84°12.61'W	76.90	2262
1131	40°25.14'N	84°12.28'W	75.70	2391
1302	41°00.07'N	84°09.85'W	76.30	2341
1304	41°01.06'N	84°09.83'W	77.30	2226
1421	41°37.74'N	84°08.86'W	75.78	2380
1505	41°59.64'N	84°06.86'W	76.10	2322
1622	42°41.76'N	83°58.95'W	77.10	2288
1855	43°55.02'N	83°26.51'W	82.00	1703
1958	44°25.49'N	83°02.49'W	82.90	1621
2101	44°47.92'N	82°44.83'W	84.50	1481
2113	44°52.39'N	82°42.01'W	85.70	1375
2205	45°12.16'N	82°31.94'W	89.20	1068

DAYTON, OHIO TETROON RELEASE

14 October 1983

Transponder S/N: 15
Launch Time: 1200 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1406	39°56.22'N	83°57.10'W	90.90	917
1466	40°00.60'N	83°37.14'W	89.80	1013
1533	40°06.96'N	83°14.92'W	85.50	1394
1935	40°51.17'N	81°04.85'W	93.40	698
2013	41°08.54'N	80°33.37'W	93.80	663
2202	41°09.66'N	79°12.72'W	94.50	597
0257	40°43.23'N	76°49.70'W	95.00	557
0309	40°42.39'N	76°44.40'W	94.80	573
0321	40°41.75'N	76°39.67'W	97.40	346
0419	40°41.03'N	76°29.95'W	97.00	377
0553	40°40.32'N	76°24.36'W	97.50	334

Transponder S/N: 18
Launch Time: 1200 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
Landing Point	45°58.00'N	72°14.00'W	---	---

Transponder S/N: 14
Launch Time: 1330 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1337	39°56.41'N	84°10.56'W	94.00	638
1355	39°56.69'N	84°00.70'W	---	---
1416	39°54.62'N	83°42.67'W	---	---
1420	39°55.72'N	83°38.09'W	92.00	817
1426	39°55.65'N	83°34.23'W	---	---
1500	39°55.33'N	83°04.59'W	---	---
1537	39°52.79'N	82°35.89'W	---	---
2035	39°32.42'N	78°53.24'W	87.30	1234
2047	39°31.03'N	78°44.32'W	87.20	1243
2058	39°28.68'N	78°38.58'W	87.80	1185
2112	39°25.45'N	78°30.60'W	87.50	1210
2121	29°22.17'N	78°19.98'W	87.10	1254
0013	38°29.59'N	77°18.30'W	87.80	1190

DAYTON, OHIO TETROON RELEASE

14 October 1983
(Con't)

Transponder S/N: 24
Launch Time: 1500 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1600	39°52.89'N	83°36.28'W	76.90	2149
1838	39°49.07'N	81°19.61'W	76.80	2154
1955	39°47.90'N	80°16.58'W	76.90	2149
2140	39°23.68'N	78°37.82'W	81.10	1785
0043	38°48.15'N	76°37.45'W	---	---

Transponder S/N: 20
Launch Time: 1500 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
Landing Point	28°40.00'N	81°21.00	---	---

DAYTON, OHIO TETROON RELEASE

17 October 1983

Transponder S/N: 8
Launch Time: 1600 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1700	39°51.92'N	84°10.71'W	90.20	978
Landing Point	40°32.50'N	87°22.00'W	---	---

Transponder S/N: 8
Launch Time: 1600 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
2256	39°52.96'N	84°14.38'W	90.70	936
2337	39°55.47'N	84°18.16'W	91.60	860
0105	39°53.63'N	84°19.87'W	91.20	896
0111	39°53.59'N	84°20.41'W	91.10	902
0121	39°53.38'N	84°20.90'W	91.10	909

Transponder S/N: 17
Launch Time: 2200 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
Landing Point	39°42.00'N	84°32.50'W	---	---

SUDBURY, ONTARIO TETROON RELEASE

19 October 1983

Transponder S/N: 21
Launch Time: 1300 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1449	46°24.00'N	80°53.57'W	92.80	746
1556	46°23.61'N	80°53.85'W	93.10	724
1600	46°23.19'N	80°53.97'W	96.70	406
1602	46°23.07'N	80°54.09'W	96.90	388
1605	46°22.90'N	80°54.15'W	96.70	406
1616	46°22.06'N	80°54.78'W	96.50	420
1736	46°12.82'N	81°04.27'W	96.75	402

Transponder S/N: 23
Launch Time: 2030 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
2220	46°20.18'N	81°04.62'W	---	---
0522	45°41.12'N	81°02.46'W	94.98	553
0600	45°40.87'N	81°02.47'W	94.77	575
Landing Point	46°29.00'N	84°23.00'W	---	---

SUDBURY, ONTARIO TETROON RELEASE

20 October 1983

Transponder S/N: 19
Launch Time: 1500 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1532	46°37.27'N	80°59.71'W	87.90	1182
1552	46°30.07'N	80°59.71'W	87.50	1216
1605	46°16.47'N	81°07.76'W	87.70	1200
1827	46°11.17'N	81°50.49'W	93.00	732
1831	46°10.83'N	81°51.93'W	92.60	767
2138	46°17.12'N	81°23.11'W	93.60	679
2143	46°16.57'N	83°25.66'W	94.60	592
0106	47°01.44'N	85°02.11'W	94.80	573
0108	47°02.09'N	85°05.74'W	94.91	561
0114	47°04.07'N	85°06.76'W	94.90	563

Transponder S/N: 29
Launch Time: 2000 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPa)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
2047	46°28.01'N	80°57.23'W	94.70	581
2050	46°27.93'N	80°58.33'W	94.50	600
2052	46°27.90'N	80°59.30'W	83.00	1613
2057	46°27.81'N	81°00.70'W	83.20	1595
2101	46°27.80'N	81°01.80'W	82.90	1614

SUDBURY, ONTARIO TETROON RELEASE

26 October 1983

Transponder S/N: 22
Launch Time: 1145 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1428	46°15.87'N	79°56.63'W	91.30	883

SUDBURY, ONTARIO TETROON RELEASE

27 October 1983

Transponder S/N: 27
Launch Time: 0245 EDT

<u>TIME</u> (EDT)	<u>LATITUDE</u> (Deg, Min)	<u>LONGITUDE</u> (Deg, Min)	<u>PRESSURE</u> (kPA)	<u>ALTITUDE</u> (m above msl)
0700	45°39.29'N	79°44.17'W	91.60	854

DAYTON, OHIO TETROON RELEASE

28 October 1983

Transponder S/N: 26
Launch Time: 1130 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1142	39°56.68'N	84°07.13'W	---	---
1148	39°57.85'N	84°01.60'W	---	---
1300	40°13.34'N	82°36.62'W	---	---
1325	40°18.96'N	82°10.54'W	---	---
1337	40°21.48'N	81°59.03'W	---	---
1402	40°28.24'N	81°35.03'W	89.80	1006
1615	41°15.46'N	79°42.21'W	90.10	989
1617	41°15.99'N	79°41.29'W	87.96	1177
1931	42°03.02'N	77°07.47'W	87.90	1182
1946	42°04.78'N	76°53.29'W	88.40	1137
2003	42°08.24'N	76°37.53'W	88.30	1147
2249	42°23.58'N	74°18.41'W	---	---

SUDBURY, ONTARIO TETROON RELEASE

29 October 1983

Transponder S/N: 29
Launch Time: 0200 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
1331	43°13.98'N	80°14.67'W	90.00	997
1344	43°21.10'N	80°15.22'W	91.30	883
1346	43°20.61'N	80°14.82'W	91.90	892
1411	43°15.18'N	80°10.99'W	---	---
1657	42°41.81'N	79°45.91'W	91.60	850
1702	42°41.49'N	79°45.69'W	92.10	805
1720	42°37.63'N	79°43.04'W	---	---
Landing Point	42°10.00'N	79°25.00'W	---	---

Transponder S/N: 30
Launch Time: 0300 EDT

<u>TIME</u> <u>(EDT)</u>	<u>LATITUDE</u> <u>(Deg, Min)</u>	<u>LONGITUDE</u> <u>(Deg, Min)</u>	<u>PRESSURE</u> <u>(kPA)</u>	<u>ALTITUDE</u> <u>(m above msl)</u>
Landing Point	43°05.00'N	78°47.30'W	---	---